

# Proposal for a Large Multipurpose Detector at Homestake

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2/10/2006

acronym? LMD

first phase: LMD-I, 100kT water Cherenkov, Fiducial:75kT

# Participants in LOI

- D. Cline, M. Diwan, K. Lande, R. Lanou, A.K. Lanou, W. Marciano
- Speaking for many others. All are welcome.
- A strategy needs to be developed to get to a 100 kT detector. This is the physics justification.
- Plan advocated is to start building a 100 kT cavity as soon as possible.

# Outline of this talk

- Will focus on LMD-I, 100 kT water Cherenkov detector.
- Physics topics:
  - Very Long Baseline Neutrino Oscillation
  - Nucleon decay
  - Astrophysical neutrinos
- Brief details of study on accelerator beams.

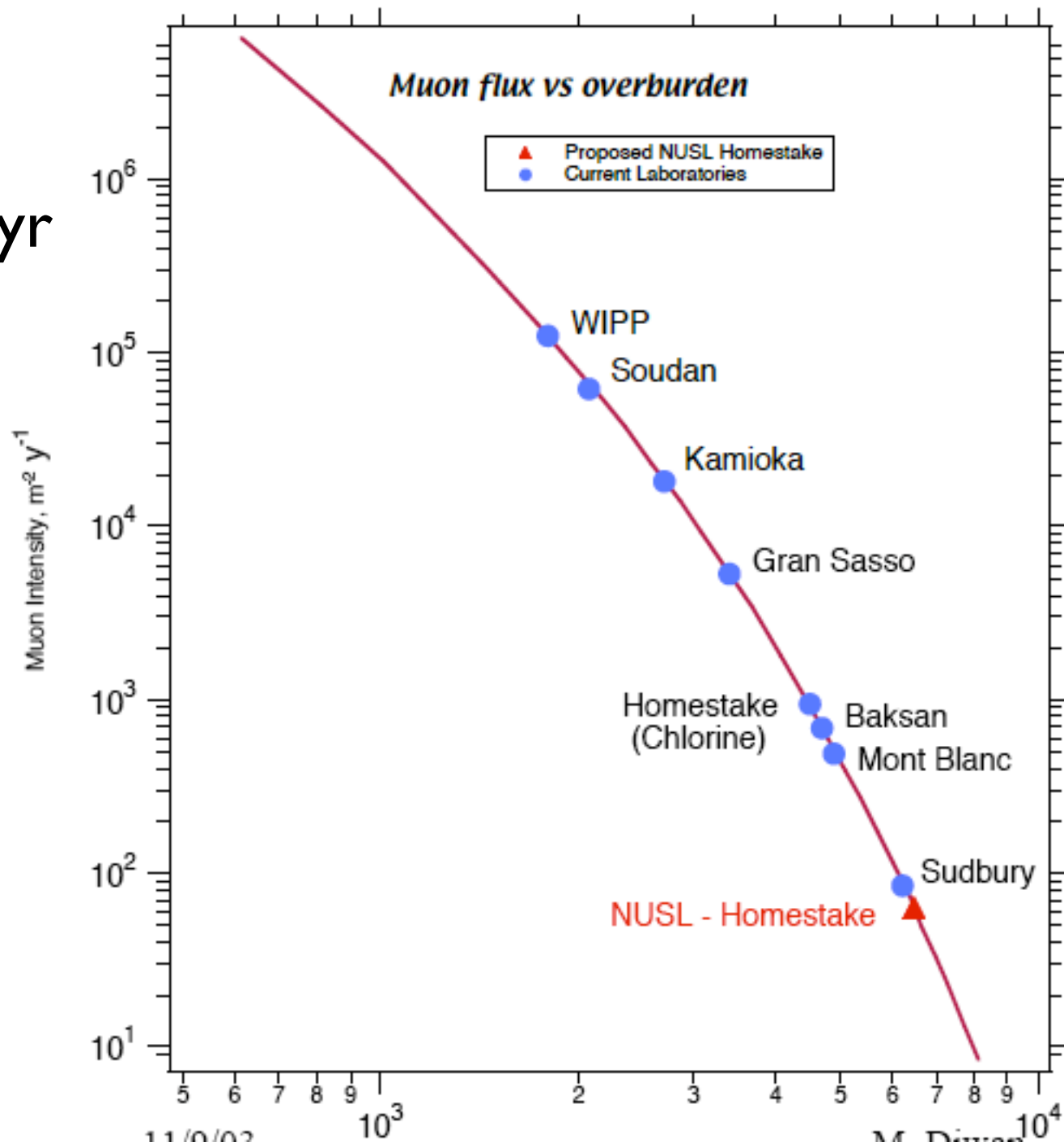
# Detector parameters

- Need 500 kT fiducial mass for proton decay, neutrino astrophysics, neutrino beam physics with CP sensitivity.
- 100 kT is initial step => 50 m dia X 50 m high tank.
- depth ? May not need anti-counter if deep enough.
- ~10% energy resolution on quasilelastics.
- Threshold of 5 MeV for solar and supernova
- Time res. ~few ns for pattern recognition.
- Good mu/e separation. <1%.
  - 1,2,3 track separation, NC rejection ~X20.

This level of performance can be obtained with water Cherenkov detector with 20-40% PMT coverage.

=> 11000 to 22000 20inch PMTs for 100kT.

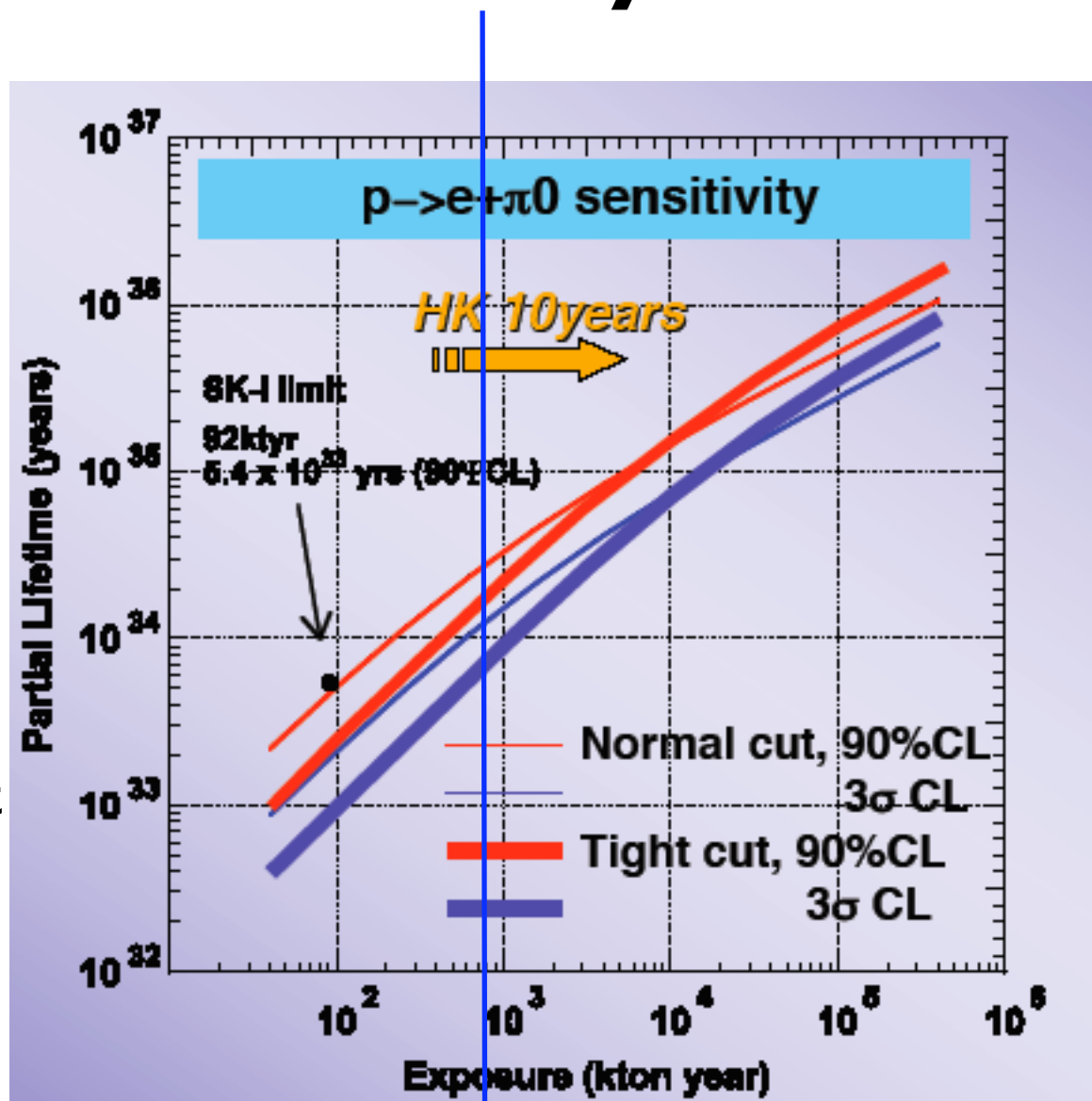
100kT  
2M muons/yr



# Nucleon decay

- Large body of work by HyperK, and UNO.
- background levels for the positron+Pion mode
  - 3.6/MTon-yr (normal)
  - 0.15/MTon-yr (tight)

LMD-100 will hit backg. in ~3yrs. It could be important to perform this first step before building bigger.



LMD-10yrs  $3 \times 10^{34}$  yrs

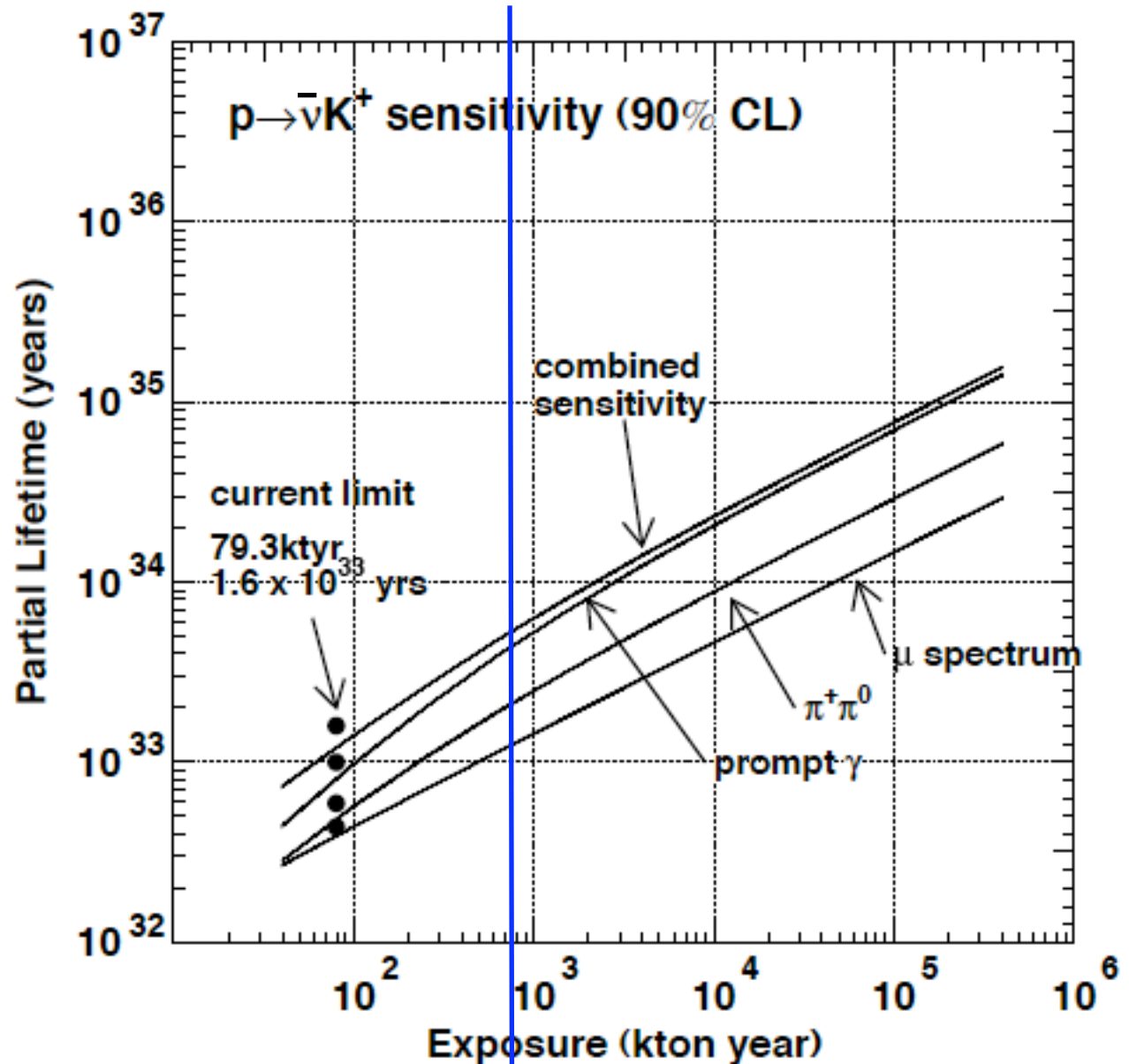
Ref: Shiozawa (NNN05)

# Other modes

Background analysis for other modes is not as advanced. But much can be learned from SK experience.

LMD-100-10yrs:  
 $5 \times 10^{33}$  yrs

Theory expectation:  
 $10^{34}$  yrs ? But  
guidance is poor.



LMD-100-10yrs  $5 \times 10^{33}$  yrs

Uno whitepaper:SBHEP01-3

# Astrophysical Neutrinos

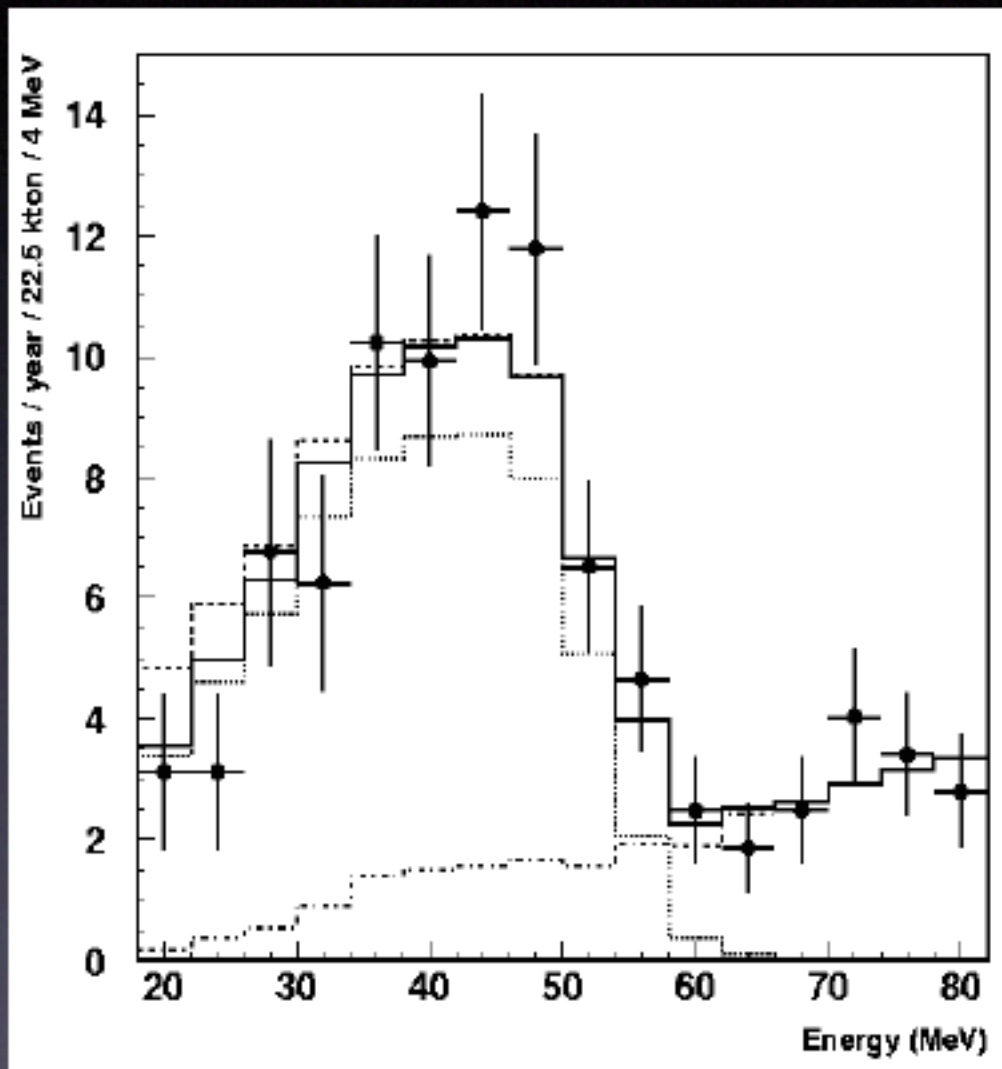
Event rates. LMD-I, assume 5 yr exposure

- Atmospheric Nus:  $\sim 10000$  muon,  $\sim 5000$  electrons. (Ref: Kajita nnn05)
- Solar Nus:  $> 63000$  elastic scattering  $E > 5\text{MeV}$  (including Osc.) (Ref: uno)
- Galactic Supernova:  $\sim 30000/10$  sec in all channels. ( $\sim 1000$  elastic events). (Ref: uno)
- Relic Supernova: (ref: Ando nnn05)
  - flux:  $\sim 5$  (1.1) /cm<sup>2</sup>/sec  $E_{\nu} > 10$  (19) MeV
  - rate: 75 (35) events over backg  $\sim 100$  !

Need analysis with these numbers



# Observational Result by Super-K



Malek et al. 2003

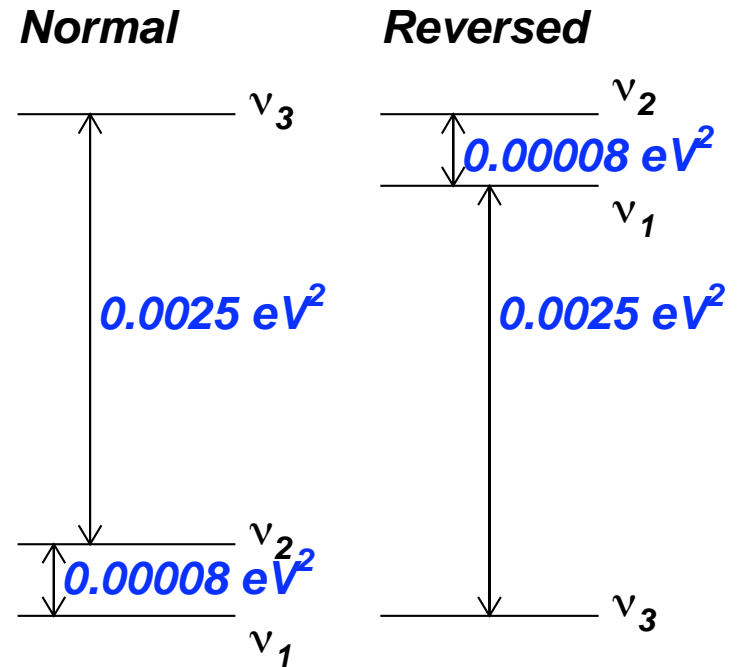
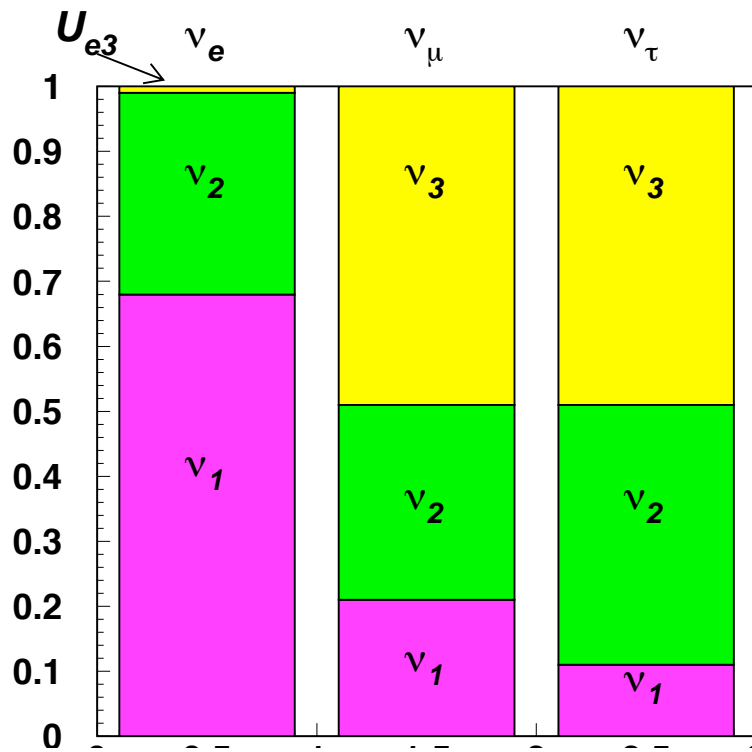
- Analysis using data for 1496 days (4.1 yr).
- As the result, they could not find positive signal.
- Upper limit on the SRN flux ( $E_\nu > 19.3$  MeV):

$$1.2 \text{ cm}^{-2} \text{ s}^{-1}$$

(90% C.L.)

Just above the prediction  
( $1.1 \text{ cm}^{-2} \text{ s}^{-1}$ )

# 3 Generation oscillations



*Difference in mass squares:  $(m_2^2 - m_1^2)$*

2-nu: 
$$P(\nu_a \rightarrow \nu_b) = \sin^2 2\theta \sin^2 \frac{1.27((m_2^2 - m_1^2)/eV^2)(L/km)}{(E/GeV)}$$

$$P(\nu_a \rightarrow \nu_b) = \sum_i |U_{ai}|^2 |U_{bi}|^2$$

3-nu:  
CP phase

$$\begin{aligned} &+2\text{Re}(U_{a1}^* U_{b1} U_{a2} U_{b2}^* \times \exp(-i\Delta m_{21}^2 L/2E)) \\ &+2\text{Re}(U_{a1}^* U_{b1} U_{a3} U_{b3}^* \times \exp(-i\Delta m_{31}^2 L/2E)) \\ &+2\text{Re}(U_{a2}^* U_{b2} U_{a3} U_{b3}^* \times \exp(-i\Delta m_{32}^2 L/2E)) \end{aligned}$$

no matter  
effects

Oscillation nodes at  $\pi/2, 3\pi/2, 5\pi/2, \dots (\pi/2)$ :  $\Delta m^2 = 0.0025 eV^2$ ,  
 $E = 1 GeV$ ,  $L = 494 km$  .      Solar :  $L \sim 15000 km$

## Next Generation Experiments

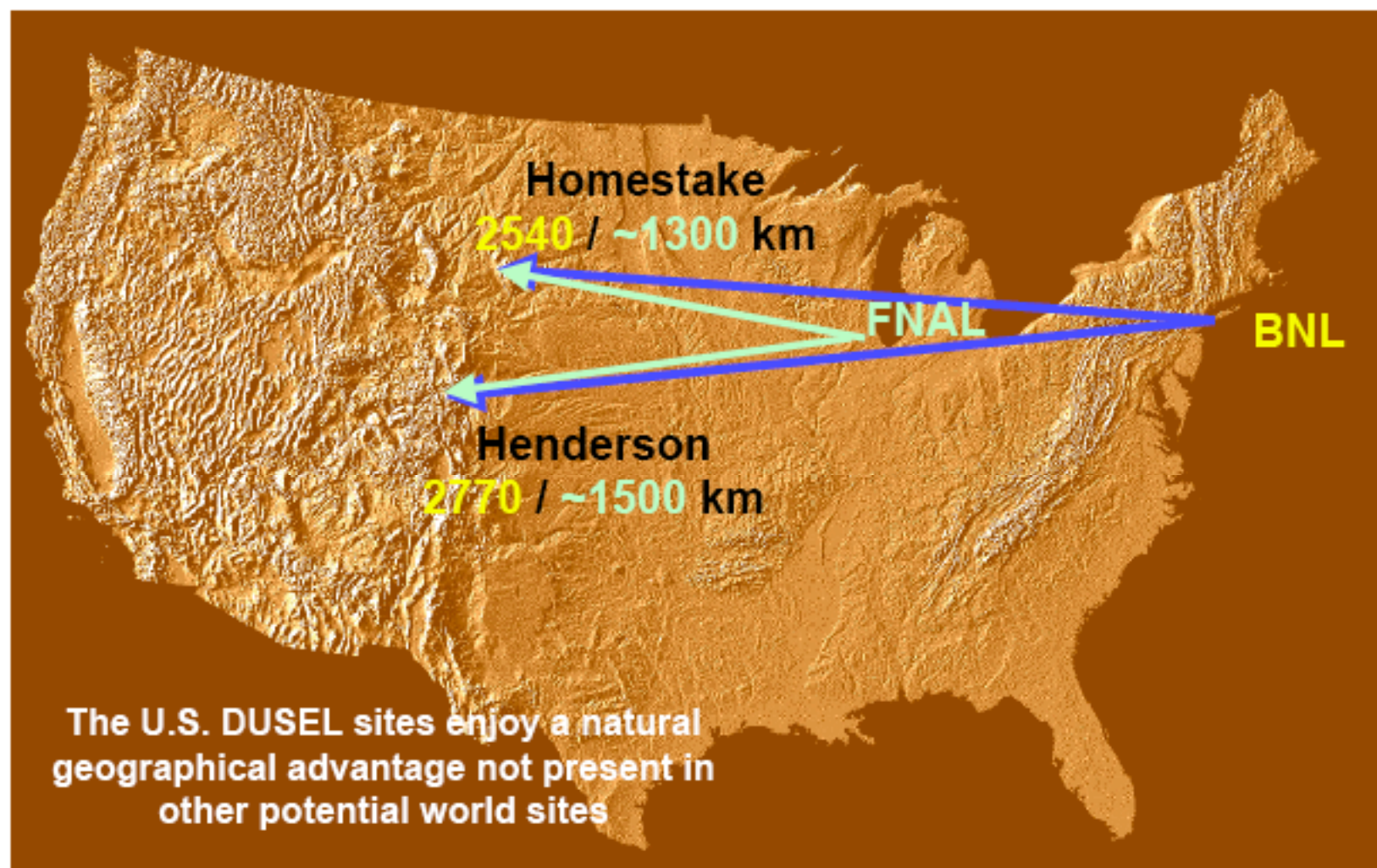
- increase sensitivity  $\sin^2 2\theta_{13}$  &  $\delta_{CP}$  significantly
- precision measurements of  $\Delta m_{32}^2$  &  $\sin^2 2\theta_{23}$
- resolve mass hierarchy (sign of  $\Delta m_{32}^2$ )
- sensitive to new physics

The heart of the 3 generation picture needs an appearance experiment with L/E that includes effects from both mass differences. This implies baseline  $> 1000$  km

This performs all remaining physics in one project



## *Super Neutrino Beam* to DUSEL Candidate Sites



# Why Very Long Baseline?

observe multiple nodes  
in oscillation pattern

👉 less dependent  
on flux normalization

neutrino travels larger  
distance through earth

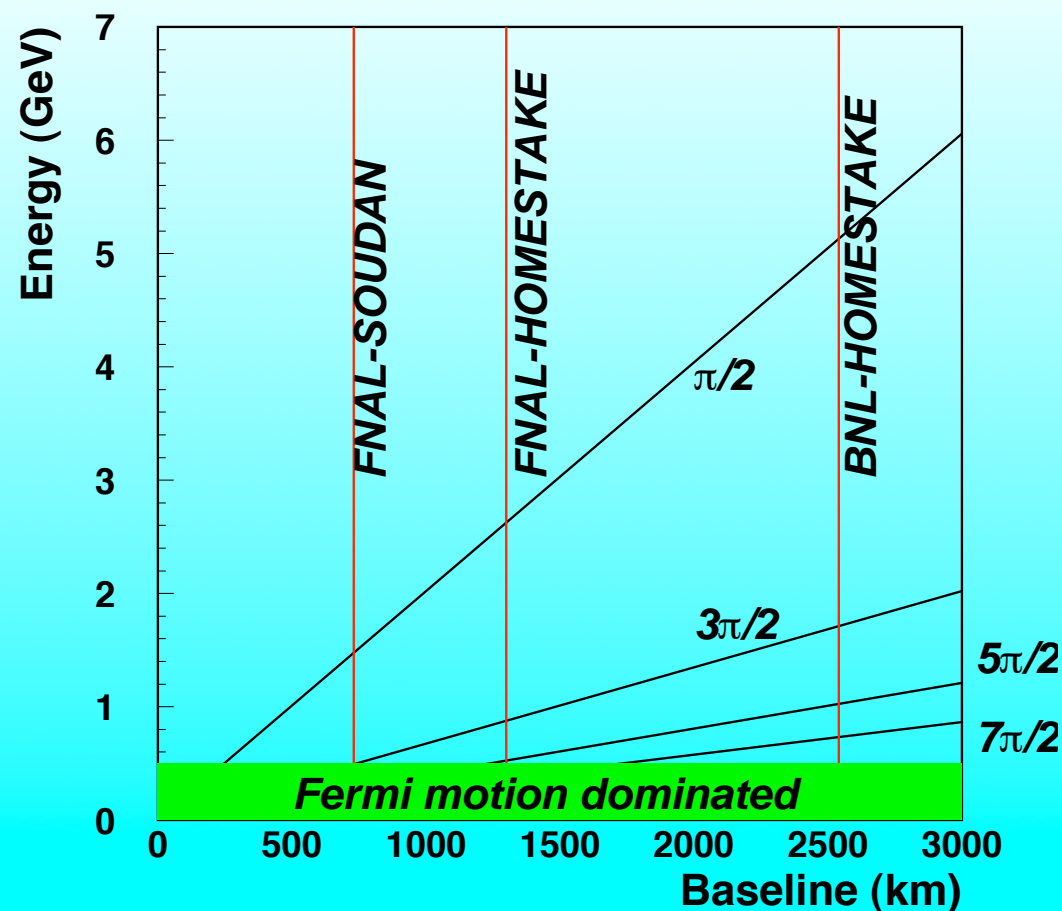
larger matter effects

flux  $\sim L^{-2}$ : lower statistics  
but: CP asymmetry  $\sim L$

sensitivity to  $\delta_{CP}$  independent of distance!

better S:B

Oscillation Nodes for  $\Delta m^2 = 0.0025 \text{ eV}^2$



(Marciano hep-ph/0108181)

## $\nu_\mu \rightarrow \nu_e$ with matter effect

Approximate formula (M. Freund)

$$\begin{aligned} P(\nu_\mu \rightarrow \nu_e) \approx & \sin^2 \theta_{23} \frac{\sin^2 2\theta_{13}}{(\hat{A} - 1)^2} \sin^2((\hat{A} - 1)\Delta) \\ & + \alpha \frac{8J_{CP}}{\hat{A}(1 - \hat{A})} \sin(\Delta) \sin(\hat{A}\Delta) \sin((1 - \hat{A})\Delta) \\ & + \alpha \frac{8I_{CP}}{\hat{A}(1 - \hat{A})} \cos(\Delta) \sin(\hat{A}\Delta) \sin((1 - \hat{A})\Delta) \\ & + \alpha^2 \frac{\cos^2 \theta_{23} \sin^2 2\theta_{12}}{\hat{A}^2} \sin^2(\hat{A}\Delta) \end{aligned}$$

$$J_{CP} = 1/8 \sin \delta_{CP} \cos \theta_{13} \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23}$$

$$I_{CP} = 1/8 \cos \delta_{CP} \cos \theta_{13} \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23}$$

$$\alpha = \Delta m_{21}^2 / \Delta m_{31}^2, \quad \Delta = \Delta m_{31}^2 L / 4E$$

$$\hat{A} = 2VE / \Delta m_{31}^2 \approx (E_\nu / \text{GeV}) / 11 \text{ For Earth's crust.}$$

# Electron neutrino appearance physics parameter extraction

For 1000 - 2000 km baseline  
effects across energy band.

	$E_\nu < 1 \text{ GeV}$	$1 < E_\nu < 2 \text{ GeV}$	$E_\nu > 2 \text{ GeV}$
$\sin^2 2\theta_{13}$	✓	✓	✓
$\text{sign}(\Delta m_{32}^2)$	-	-	✓/✓/✓
$\delta_{CP}$	✓	✓/✓	✓
solar	✓/✓/✓	✓	-

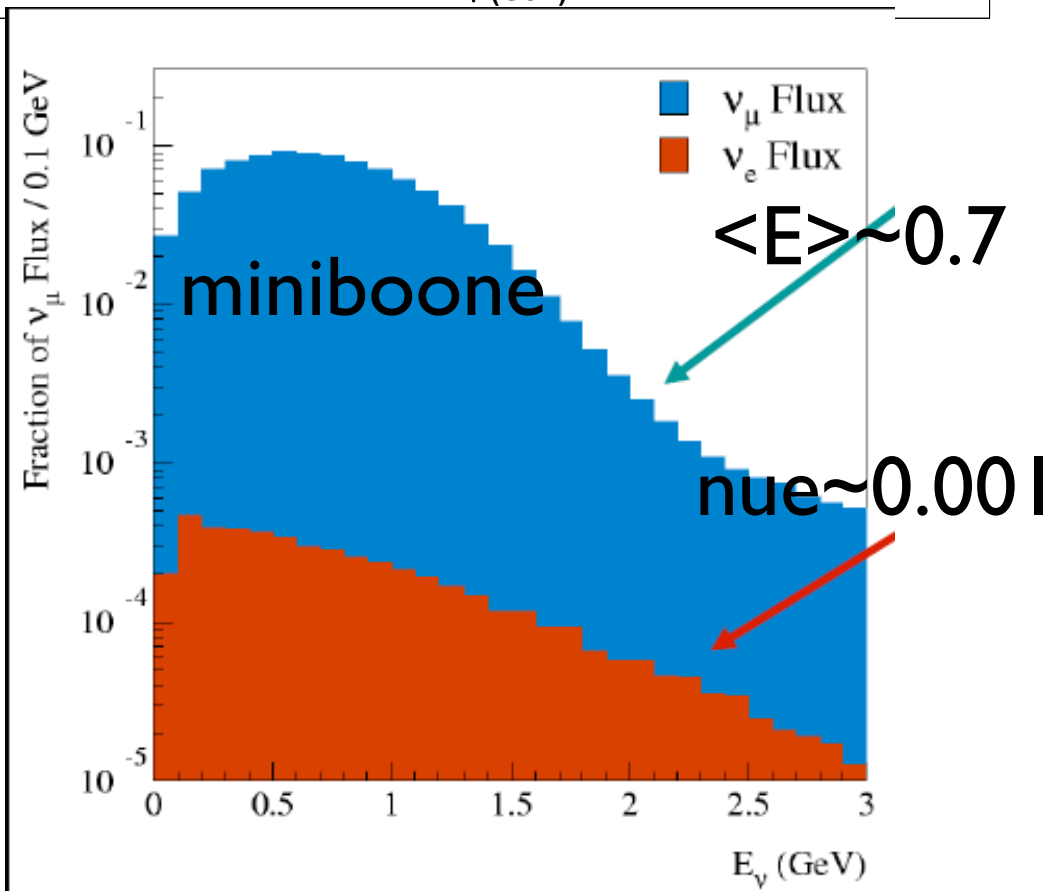
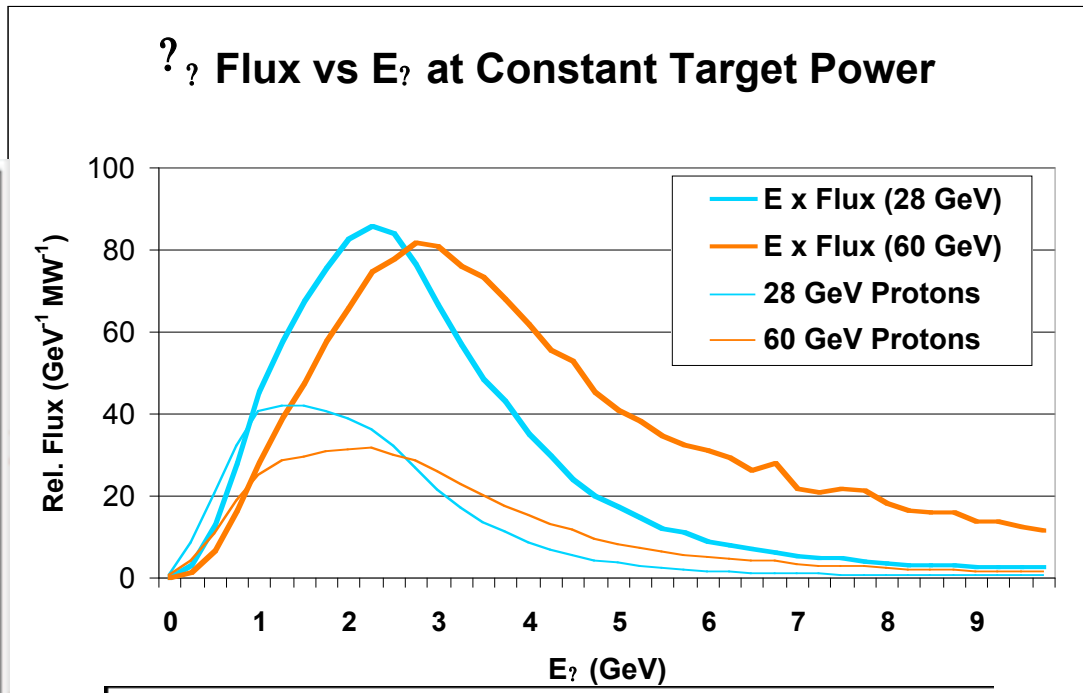
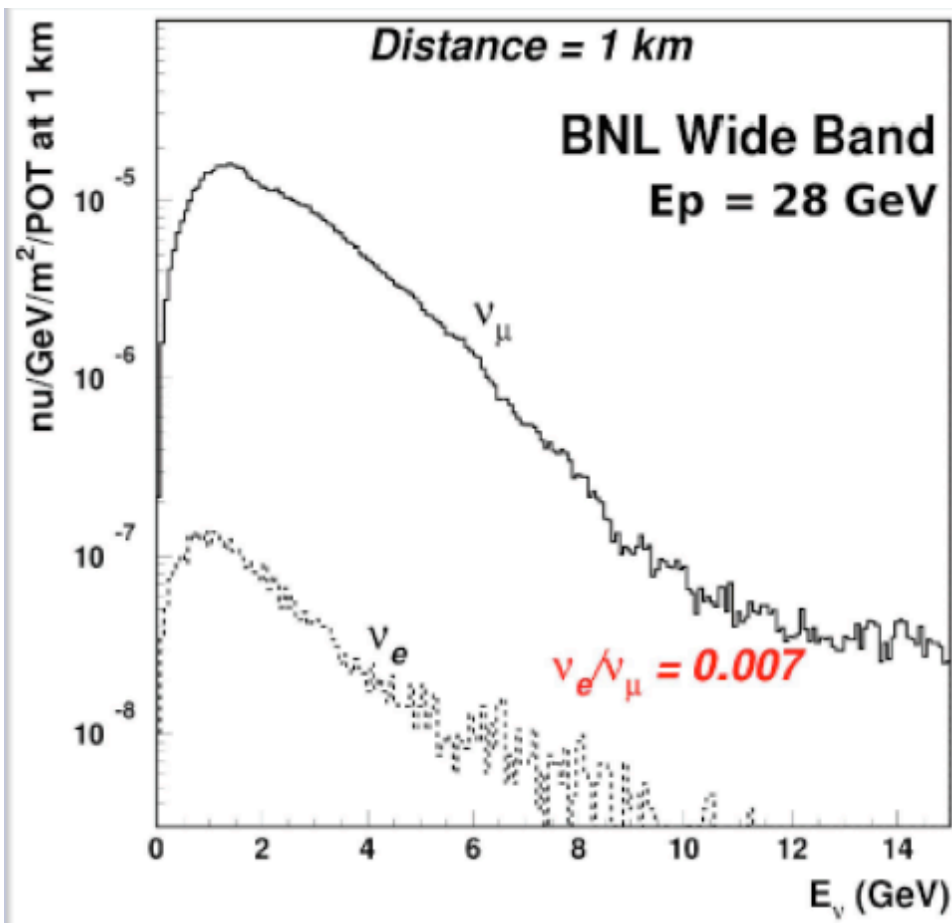
- It's a complex picture with many effects!
- But, effects have different strength at different energies.
- Measuring across the wide energy band makes it possible to sort them out.

# US possibilities for beam

Source	Proton beam energy	Proton beam power
FNAL MI (McGinnis upgrade)	$E_p=8\text{-}120\text{ GeV}$	1-2 MW X ( $E_p/120\text{ GeV}$ )
FNAL MI (with 8GeV LINAC)	$E_p=8\text{-}120\text{ GeV}$	2 MW @ any $E_p$
BNL-AGS (upgrade 2.5- 5 Hz)	$E_p=28\text{ GeV}$	1-2 MW



# Flux shapes



# US possible baselines

Source	Detector	Distance	Depth	Comment
FNAL	Soudan	735 km	2300ft	High E beam exists, not DUSEL site
FNAL	Homestake	1290 km	7700ft	no beam, DUSEL site, capable of large exca.
FNAL	Henderson	1500km	5000 ft	no beam, DUSEL site, capable of large exca.
BNL	Soudan	1711 km	2300 ft	--
BNL	Homestake	2540km	7700 ft	study of beam and physics exists and documented
BNL	Hendersn	2767km	5000 ft	--

# Event rates

Source-det	Detector size	beam E and power	Event rate for neutrino running
FNAL-HS(1290)	100kT	0.5MW@60GeV	~30000CC ~10000NC
FNAL-Hend(1500)	100kT	0.5MW@60GeV	~22000 ~7500
FNAL-HS(1290)	500kT	1MW@28GeV	194000CC 66000NC
BNL-HS(2540)	500kT	1MW@28GeV	50000CC 17000NC
FNAL-HS(1290)	200kT	2MW@8GeV using Miniboone data	2188 CC 850 NC
NOVA(810)	30kT	2X0.65MW@120	~20000 CC ~6000 NC

$5 \times 10^7$  sec of running assumed = 2 years at FNAL

# $\nu_\mu$ disappearance

## neutrino running:

1MW beam

0.5Mt water Cerenkov d

1290km distance

5e7s running time

190000 tot CC events

determine  $\Delta m^2_{32}$

&  $\sin^2 2\theta_{23}$  to 1%

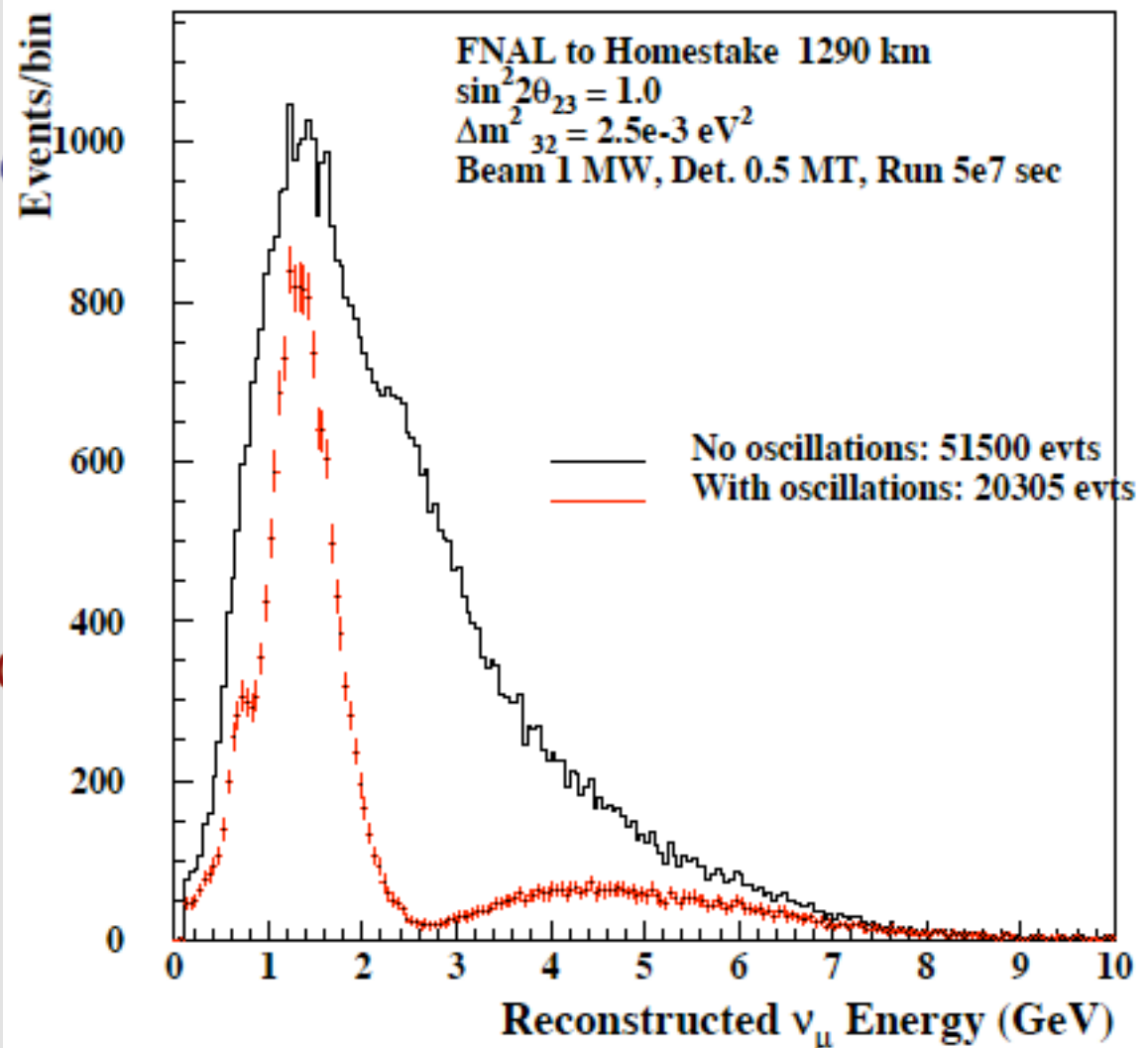
systematics dominated

## anti-neutrino running:

same as  $\nu$  but with  
2MW beam

- including anti- $\nu$  running:
- CPT test possible
  - errors below 1% achievable

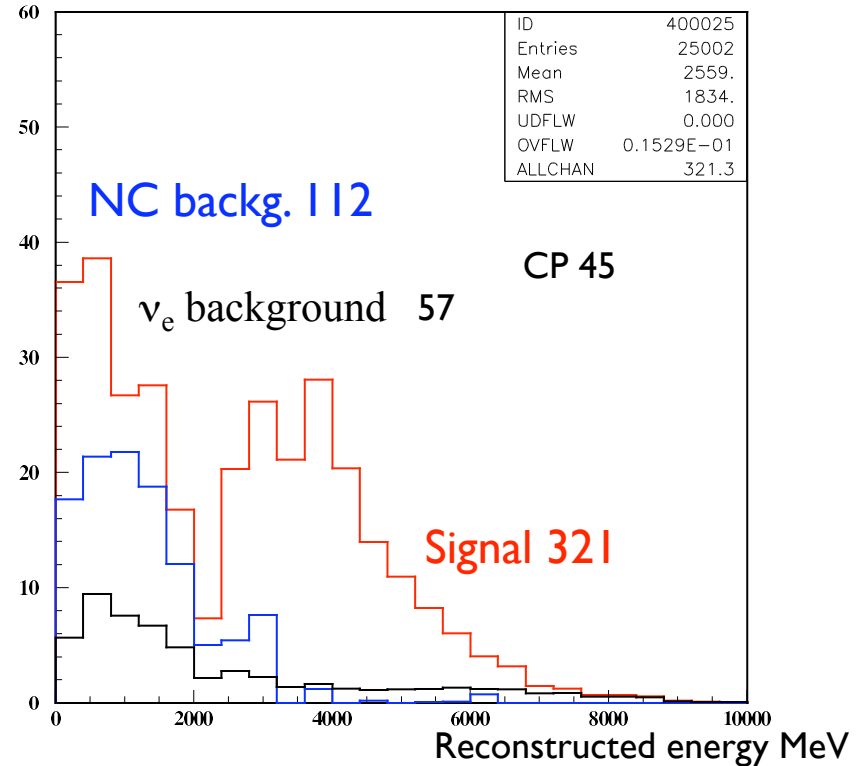
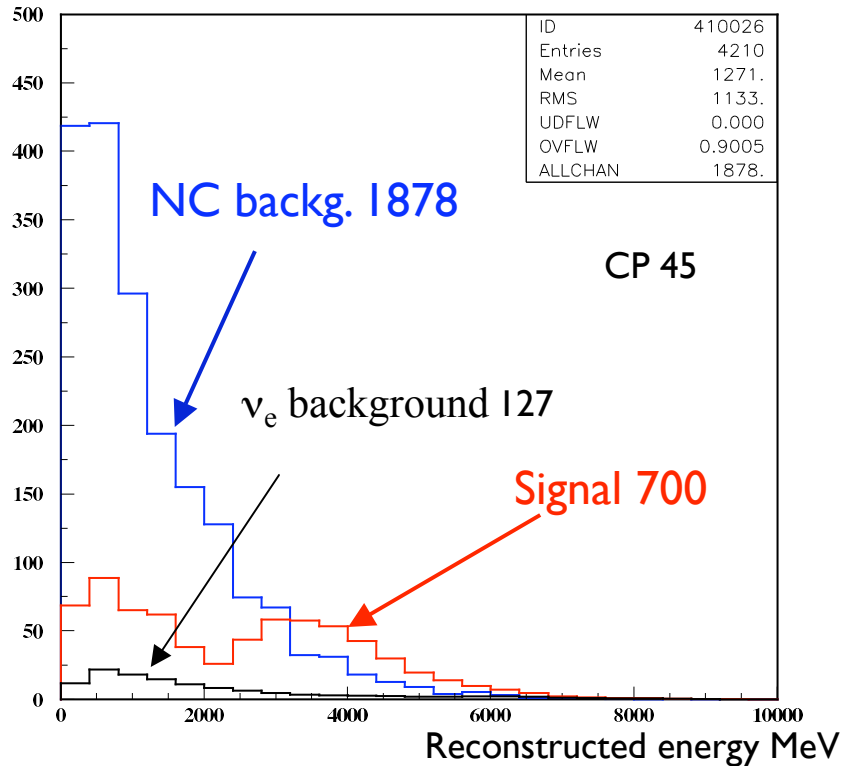
## $\nu_\mu$ disappearance



# Complete water Cherenkov detector simulations progress

$\nu_e$  CC for signal ; all  $\nu_{\mu,\tau,e}$  NC ,  $\nu_e$  beam for background

▪  $\Delta m^2_{21} = 7.3 \times 10^{-5} \text{ eV}^2$ ,  $\Delta m^2_{31} = 2.5 \times 10^{-3} \text{ eV}^2$  ▪  $\sin^2 2\theta_{ii}(12,23,13) = 0.86/1.0/0.04$ ,  $\delta_{CP} = +45, +135, -45, -135^\circ$



Select single ring events and select electrons

Signal/backg = 700/2005



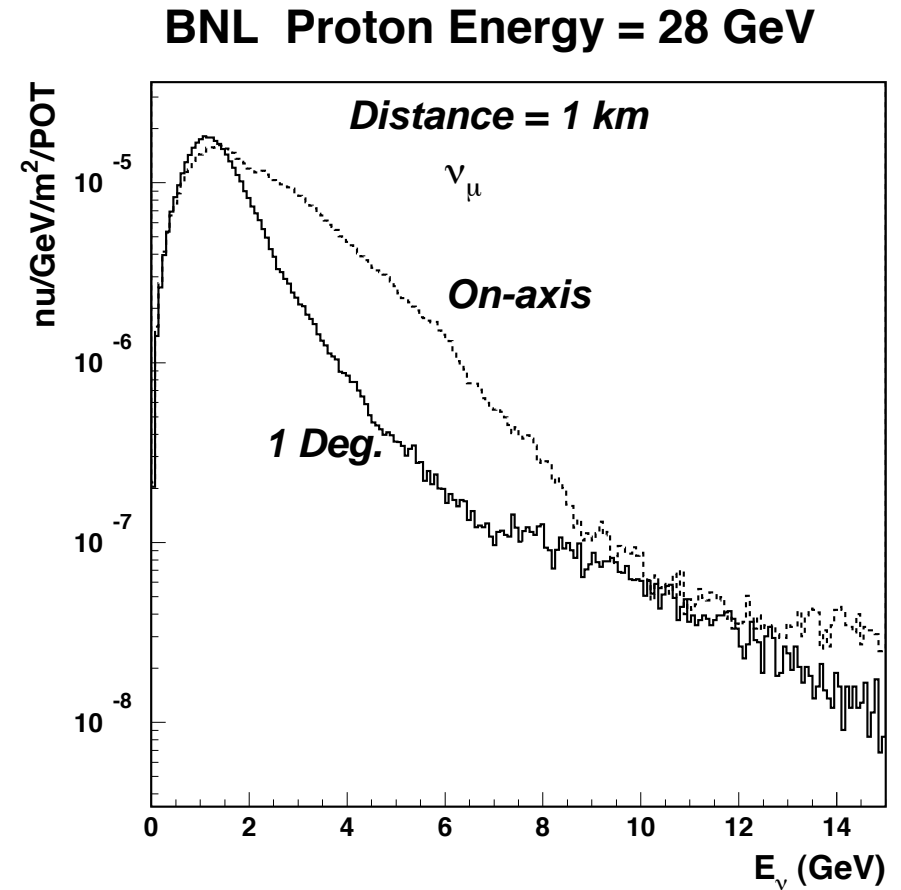
Perform analysis of single electron pattern, likelihood cut retaining ~50% of signal.

Signal/back = 321/169

C. Yanagisawa (Stony Brook), 3<sup>rd</sup> BNL/UCLA workshop  
<http://www.physics.ucla.edu/hep/proton/proton2005.htm>

# Off axis for FNAL-HS ?

1. 4 meter diameter tunnel allows for this option.
2. Large ( $\sim 1.3$  m) movement needed at the target station. Main difficulty is moving proton beam.
3. Allow horizontal movement of target station including shielding (1000 ton). Solutions exist.
4. Could build both on-axis and off-axis options from the start.



Already been designed at BNL.

# $\nu_e$ Appearance

## backgrounds:

- beam  $\nu_e$
- NC  $\nu_\mu$

## neutrino running:

measure  $\sin^2 2\theta_{13}$  and  $\delta_{CP}$   
for  $\sin^2 2\theta_{13} > 0.01$   
resolve mass hierarchy

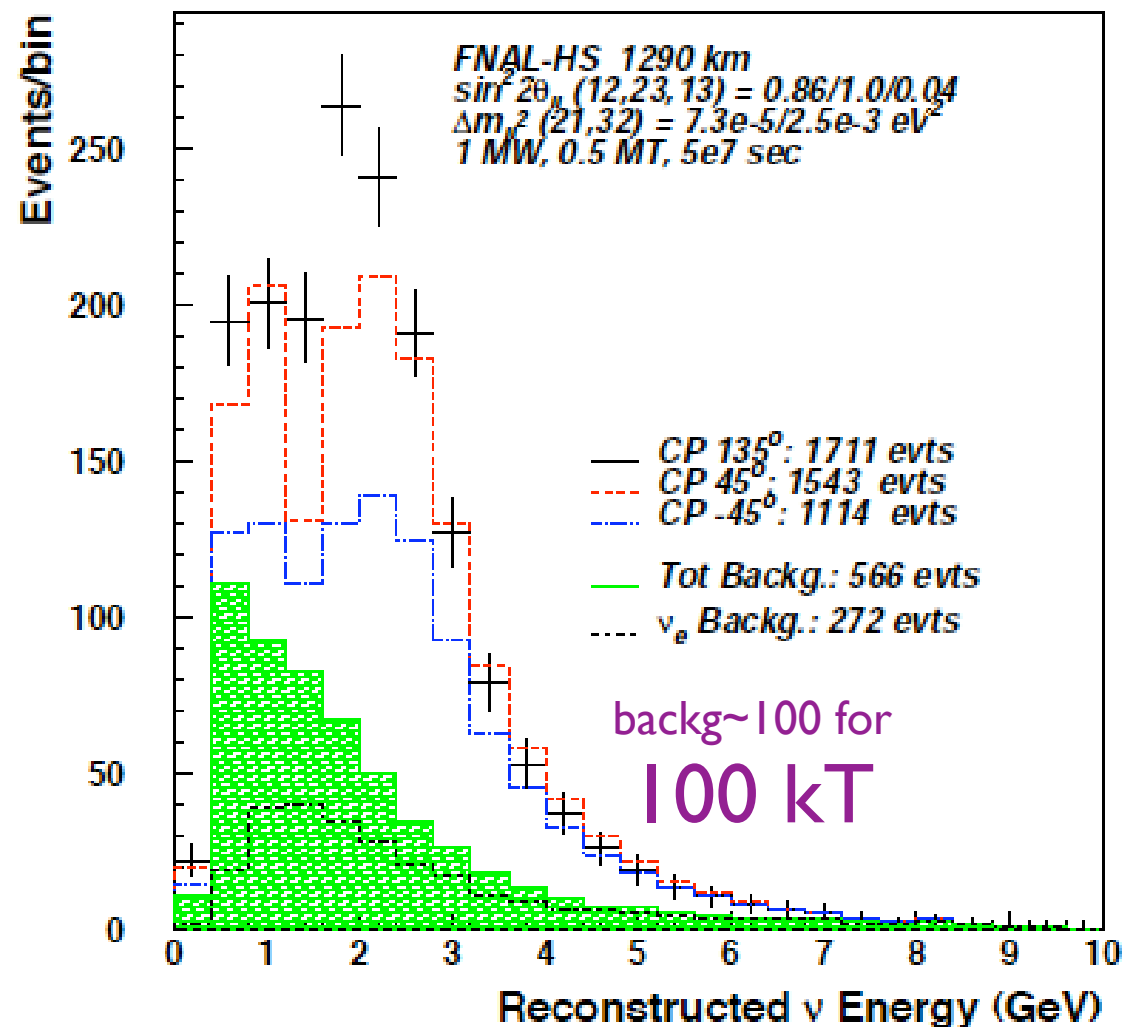
## include anti-neutrino run:

exclude  $\sin^2 2\theta_{13} > 0.003$

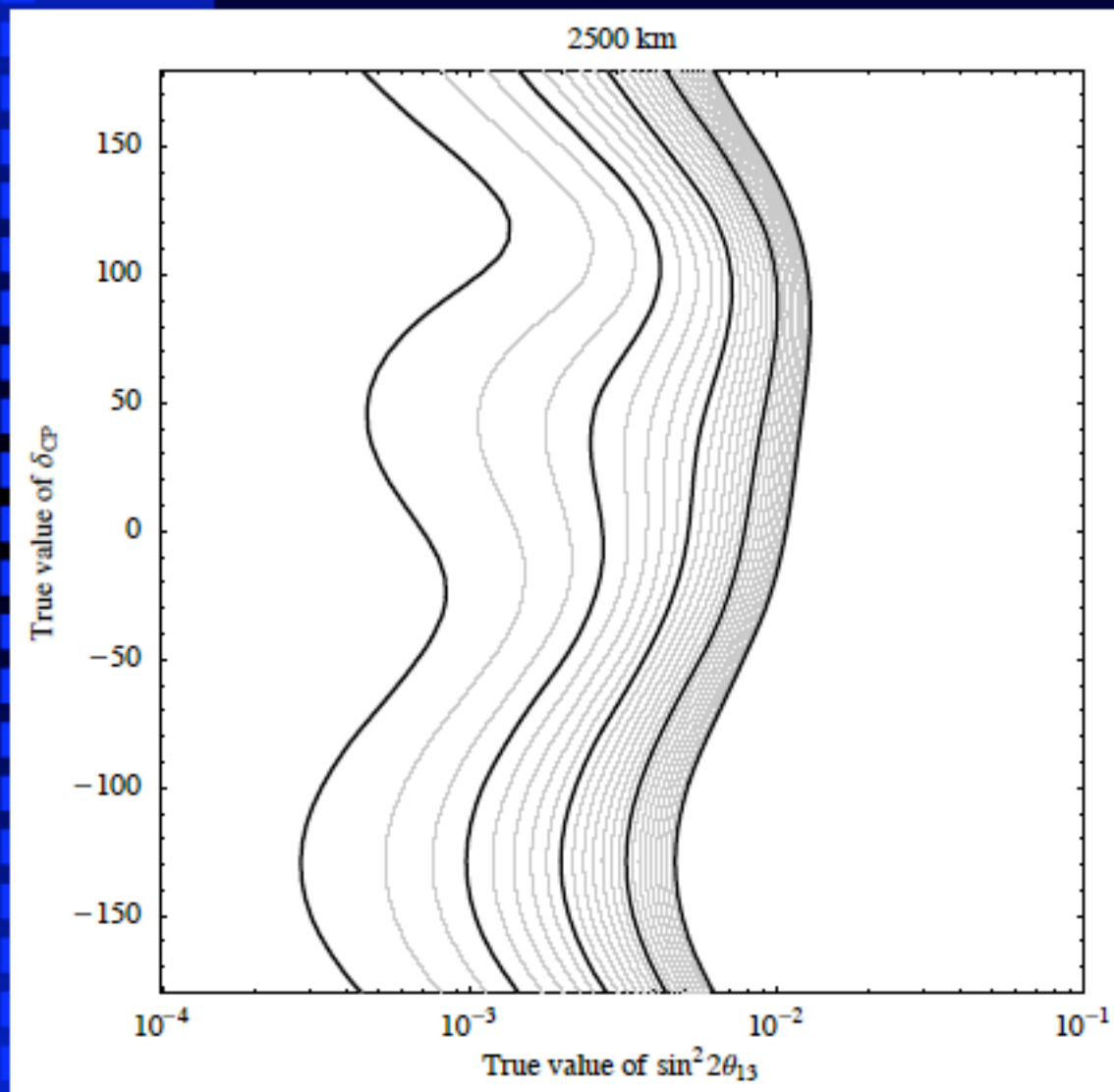
if  $\sin^2 2\theta_{13}$  too small  $\rightarrow \delta_{CP}$  measurement not possible

observation  $\nu_e$  appearance possible through solar term

## $\nu_e$ APPEARANCE



# Discovery of $\theta_{13}$

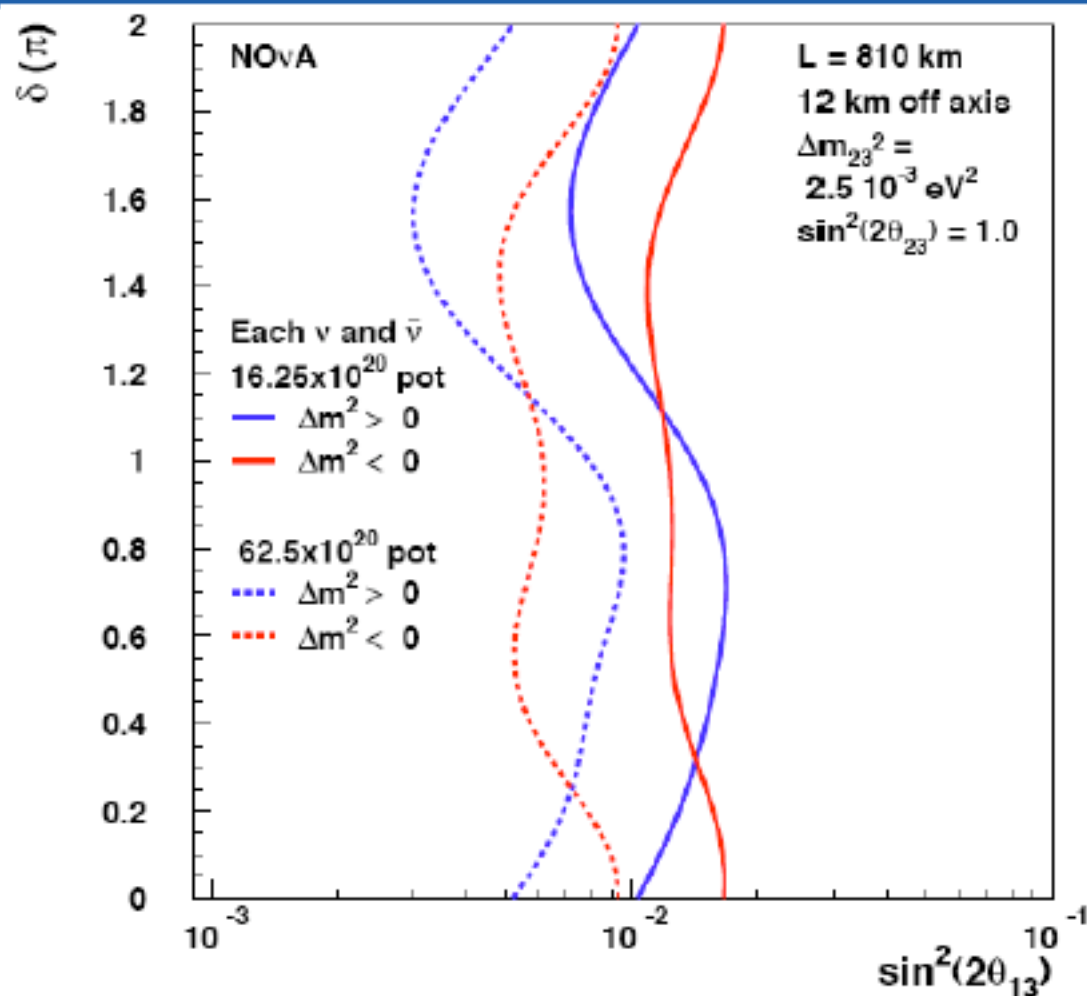


- simulate data for  $\delta$  and  $\theta_{13} \neq 0$
- try to fit them with  $\theta_{13} = 0$
- repeat the fit for the wrong hierarchy
- take the smallest  $\chi^2$



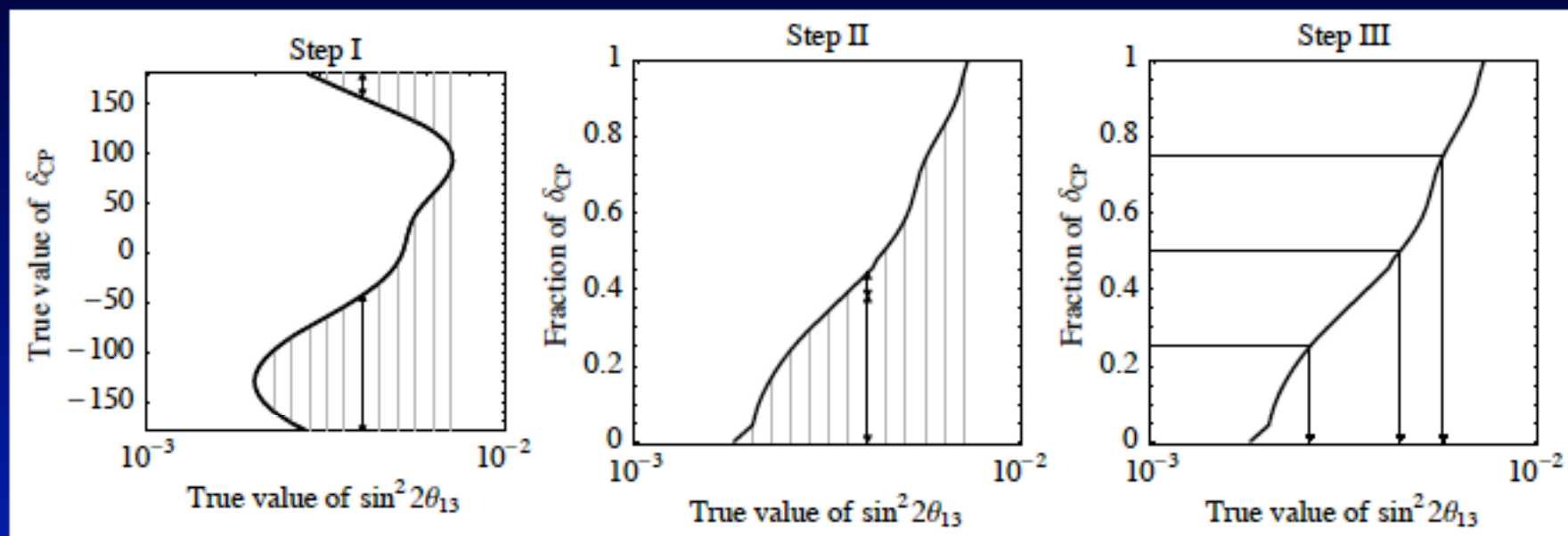


# 3 $\sigma$ Sensitivity to $\theta_{13} \neq 0$ Comparison with Proton Driver



2.5 yr each  
 $\nu$  and  $\bar{\nu}$  run

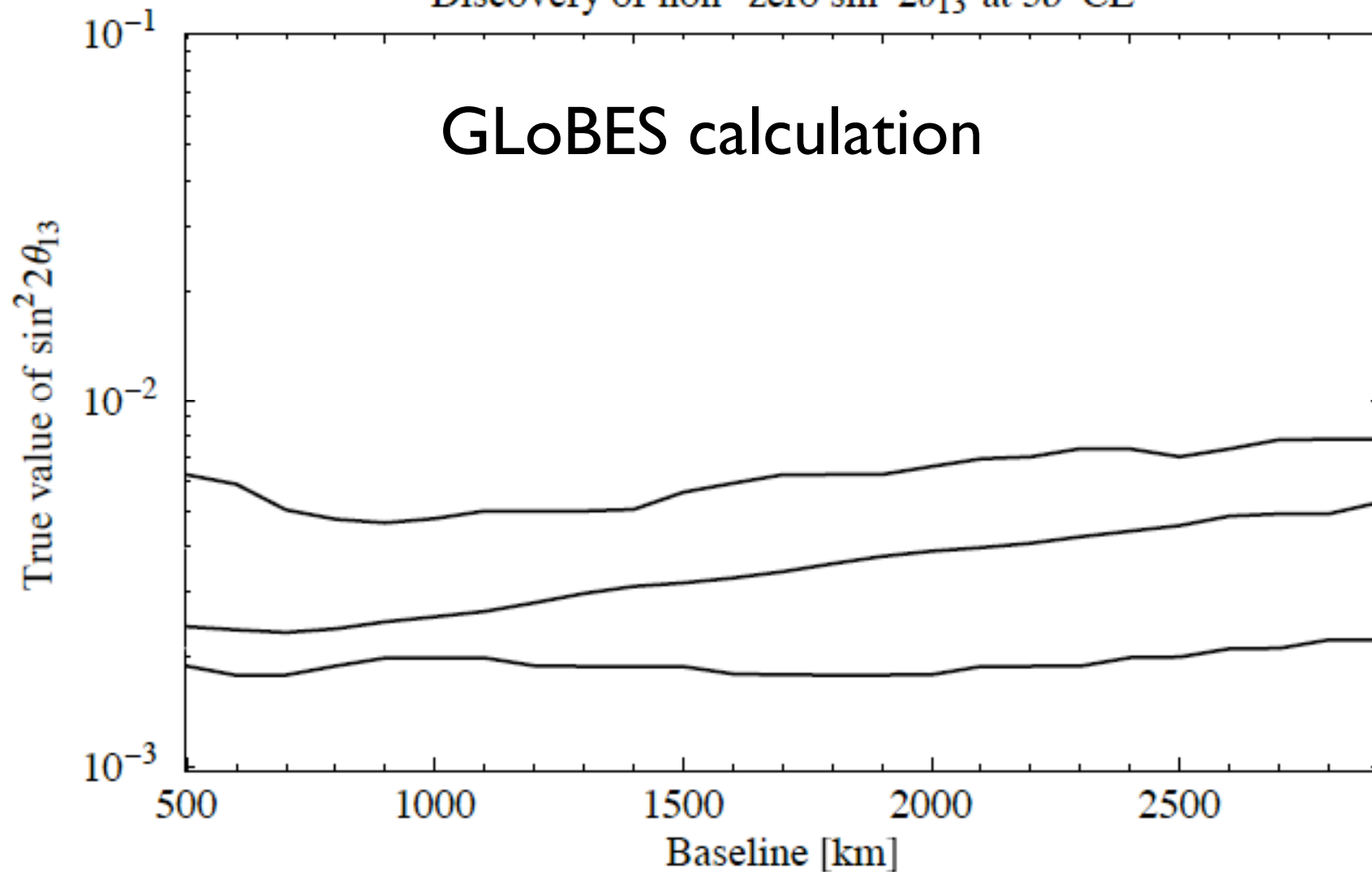
# CP fraction



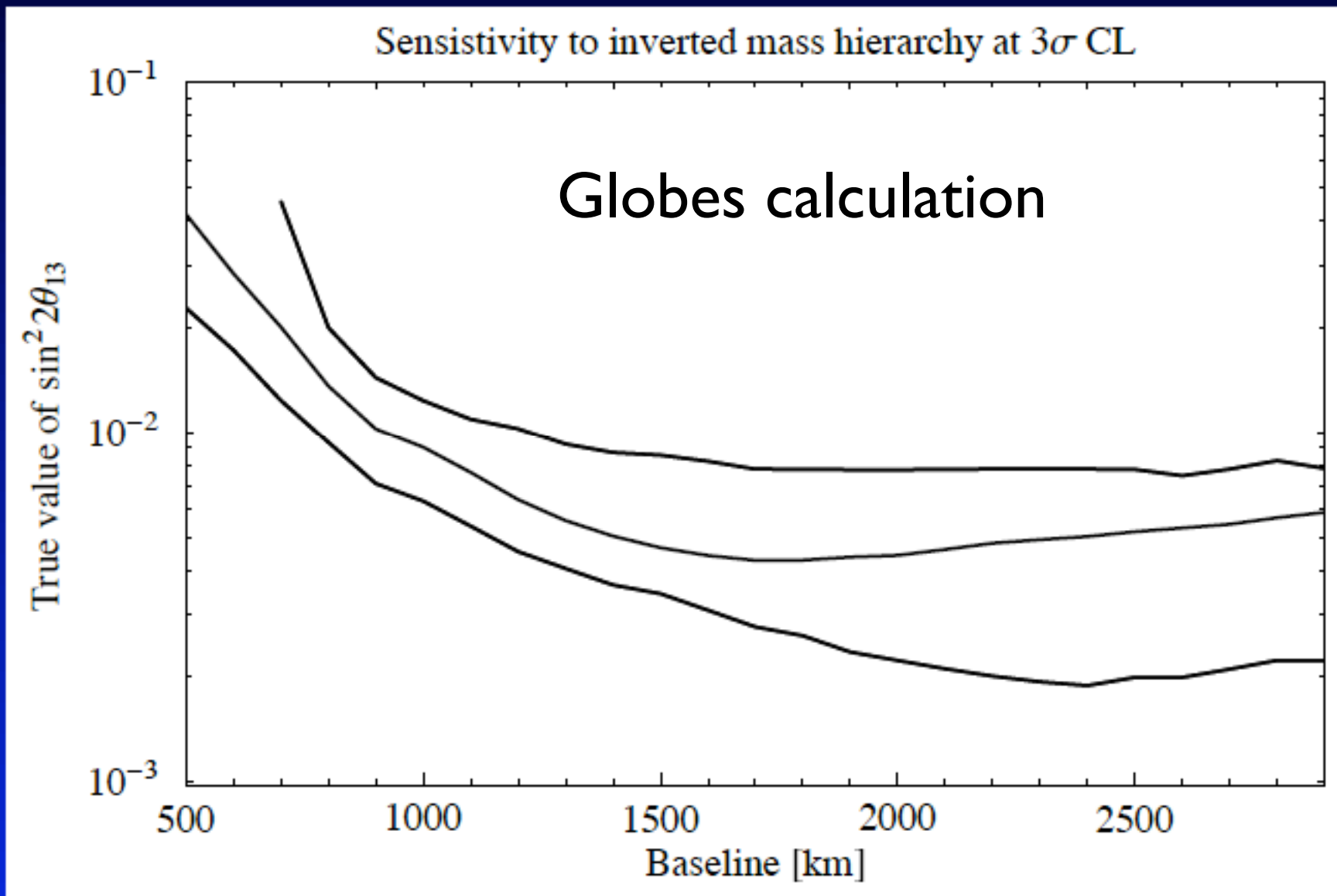
- reduces 2D plot to 3 points
- allows unbiased comparison
- allows risk assessment
- $CPF = 1$ , worst case – guaranteed sensitivity
- $CPF = 0$ , best case

Discovery of non-zero  $\sin^2 2\theta_{13}$  at  $3\sigma$  CL

GLOBES calculation

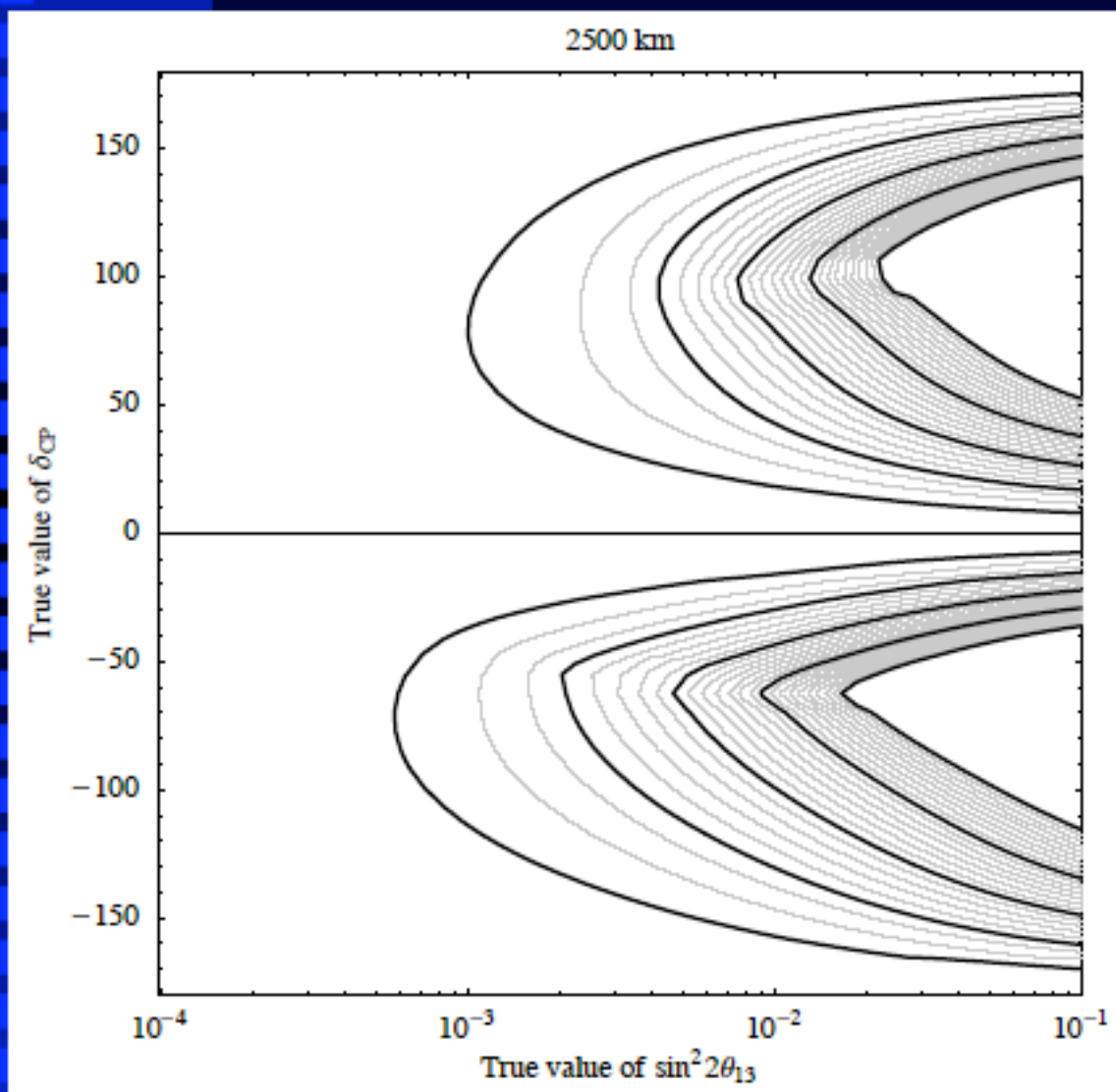


- weak baseline dependence



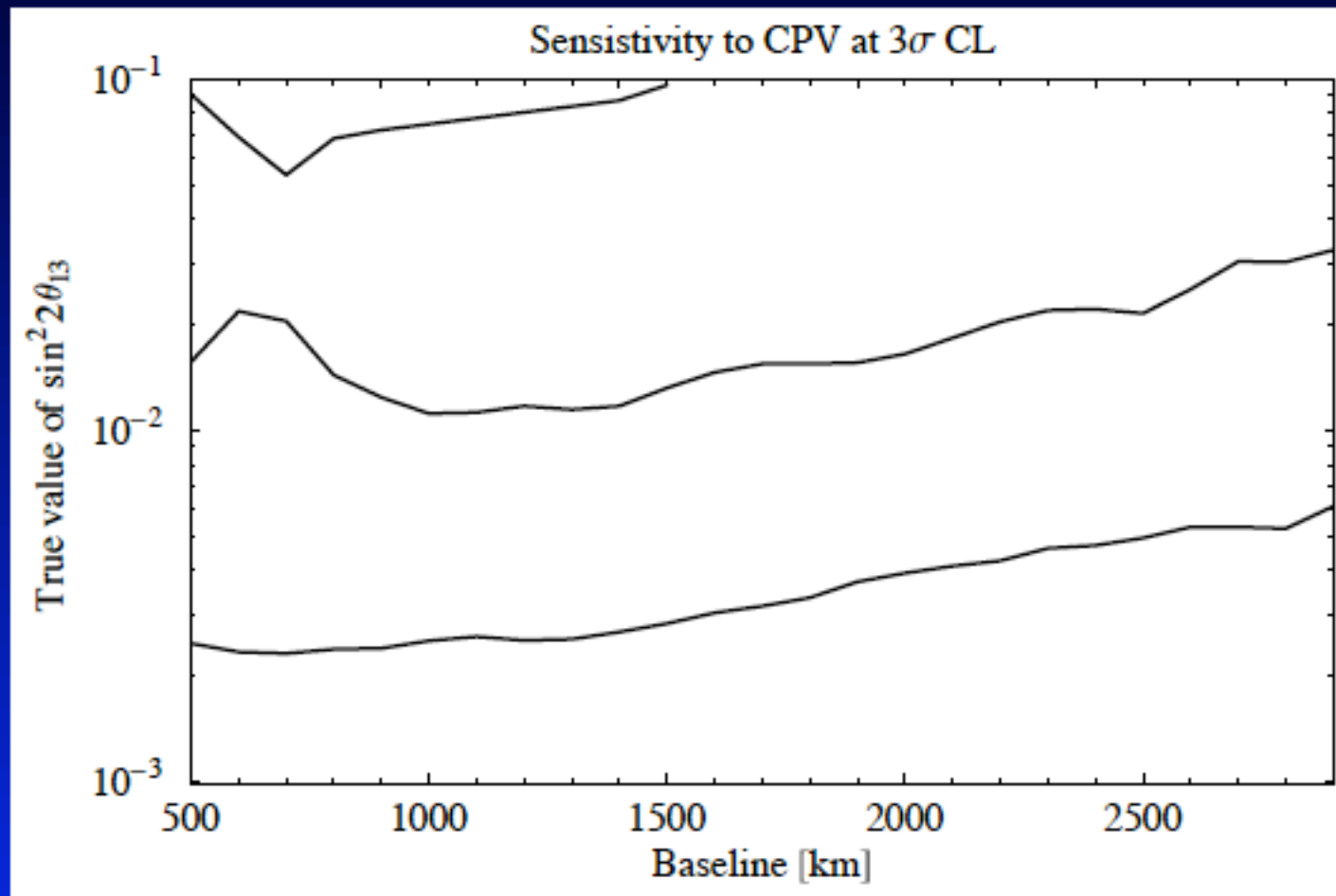
- long baselines are clearly favored

# Discovery of CP violation



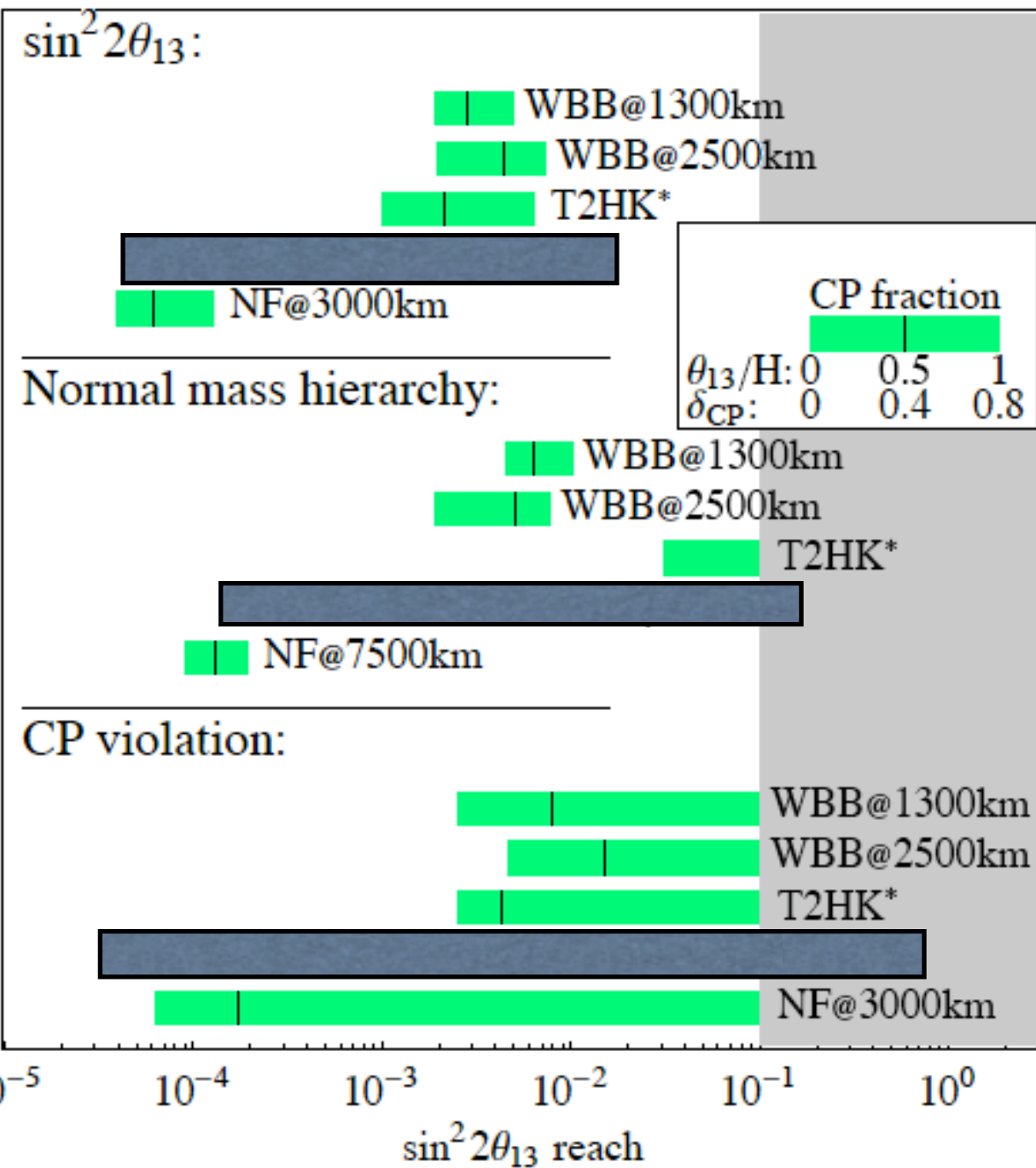
- simulate data for  $\delta \neq 0, \pi$  and  $\theta_{13}$
- try to fit them with  $\delta = 0, \pi$
- repeat the fit for the wrong hierarchy
- take the smallest  $\chi^2$

# Baseline dependence



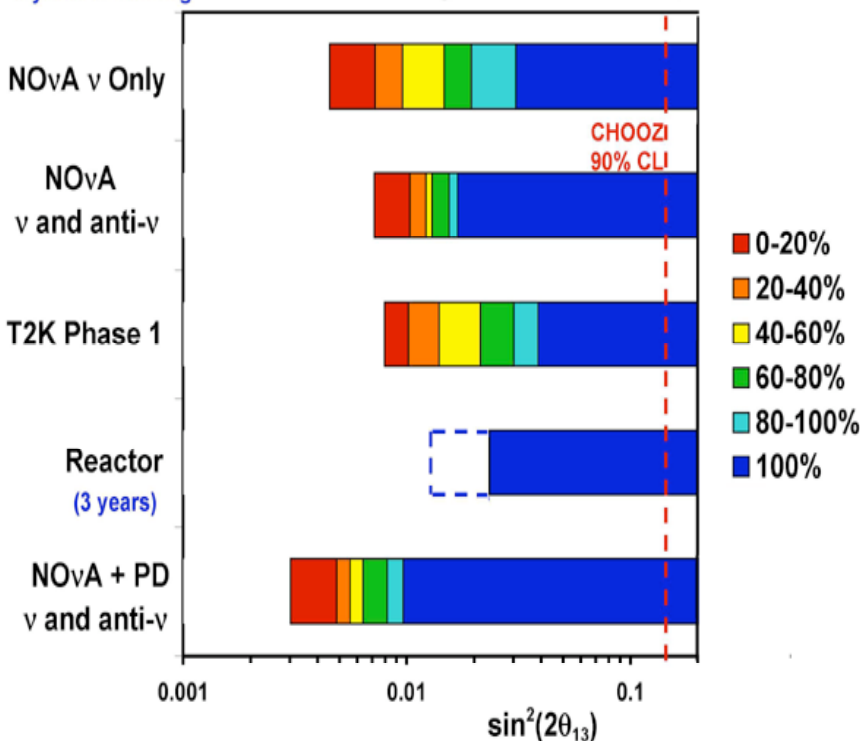
- baselines between 1000 and 2000 km are very similar

## Comparison of discovery reaches ( $3\sigma$ )



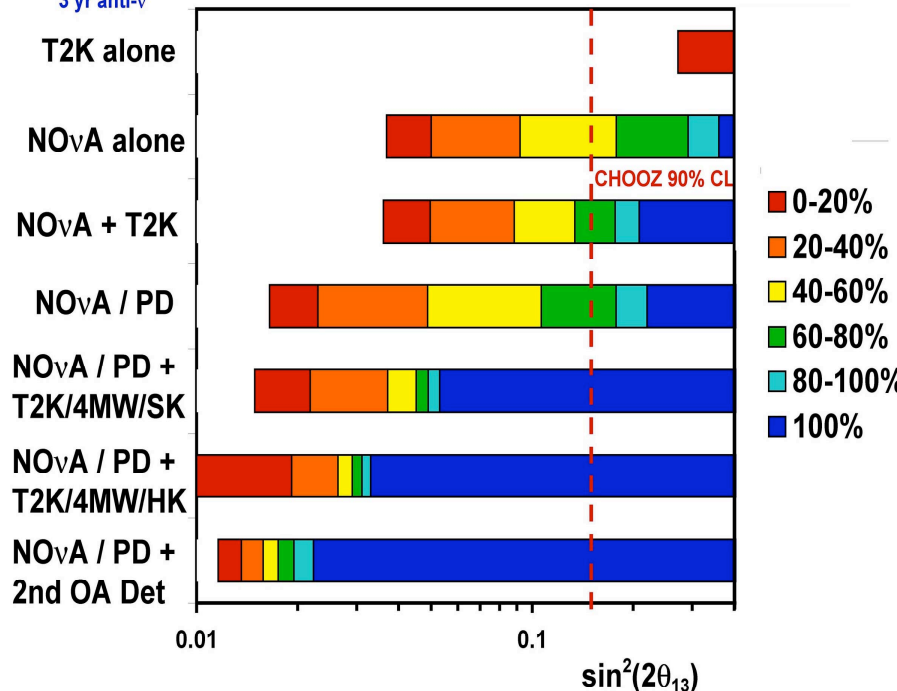
## 3 $\sigma$ Discovery Limits for $\theta_{13} \neq 0$

5 years of running



## 95% CL Determination of the Mass Ordering

3 yr  $\nu$  and  
3 yr anti- $\nu$



## Summary

- Physics case for a 100 kT detector at Homestake.
- nucleon decay, astrophysical neutrinos, long baseline.
- Important work performed on detector background issue.
- Lowest risk most cost effective option for a long baseline second generation experiment.
- If sufficiently long L/E, then you will see electron appearance through the solar term.